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Nonlocal spin Hall effect and spin-orbit interaction in nonmagnetic metals

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Abstract

Spin Hall effect in a nonlocal spin-injection device is theoretically studied. Using a nonlocal spin-injection technique, a pure spin current is created in a nonmagnetic metal (N). The spin current flowing in N is deflected by spin-orbit scattering to induce the Hall current in the transverse direction and accumulate charge at the edges of N, yielding the spin-current induced Hall effect. We propose a method for extracting the spin-orbit coupling parameter in nonmagnetic metals via the nonlocal spin-injection technique.

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There has been growing interest in spin transport in magnetic nanostructures, because of potential applications to spin electronic devices [1]. Recent experimental studies have demonstrated that the spin polarized carriers injected from a ferromagnet (F) into a nonmagnetic material (N) such as a normal metal [2,3,4,5] and superconductor [6,7] create a spin accumulation in N. In this paper, we consider a nonlocal spin-injection Hall device, and discuss the anomalous Hall effect (AHE) in the presence of spin current (or charge current) flowing in N, taking into account *side jump* and *skew scattering*.

The basic mechanism for AHE is the spin-orbit interaction in N, which causes a spin-asymmetry in the scattering of conduction electrons by impurities; up-spin electrons are preferentially scattered in one direction and down-spin electrons in the opposite direction. Spin injection techniques makes it possible to induce AHE in *nonmagnetic* conductors. When spin-polarized electrons are injected from F to N, these electrons moving in N are deflected by the spin-orbit scattering to induce the Hall current in the transverse direction and accumulate charge at the edges of N, yielding the spin-current induced spin Hall effect (SHE) [8,9,10].

Using the Boltzmann transport equations which incorporates the spin-asymmetric scattering of conduction electrons by nonmagnetic impurities in N within the Born approximation, we can derive the "total" spin and charge currents flowing in N [10,11]

$$\mathbf{J}_s = \mathbf{j}_s + \mathbf{j}_s^{\rm H}, \qquad \mathbf{J}_q = \mathbf{j}_q + \mathbf{j}_q^{\rm H}. \tag{1}$$

where $\mathbf{j}_s = -(\sigma_{\rm N}/e)\nabla\delta\mu_{\rm N}$ and $\mathbf{j}_q = \sigma_{\rm N}\mathbf{E}$ are the *longitudinal* spin and Ohmic currents, $\sigma_{\rm N} = 2e^2N(0)D$ is the electrical conductivity, $\delta\mu_{\rm N} = \frac{1}{2}(\mu_{\rm N}^{\uparrow} - \mu_{\rm N}^{\downarrow})$ is the chemical potential shift, $\mu_{\rm N}^{\sigma}$ is the chemical potential of electrons with spin σ, and D is the diffusion constant. The second terms in Eq. (1) are the transverse spin and charge Hall currents caused by spin-orbit scattering:

$$\mathbf{j}_s^{\rm H} = \alpha_{\rm H}\left[\hat{\mathbf{z}} \times \mathbf{j}_q\right] = \alpha_{\rm H}\sigma_{\rm N}\left(\hat{\mathbf{z}} \times \mathbf{E}\right), \tag{2}$$

$$\mathbf{j}_q^{\rm H} = \alpha_{\rm H}\left[\hat{\mathbf{z}} \times \mathbf{j}_s\right] = -\frac{\alpha_{\rm H}\sigma_{\rm N}}{e}\left(\hat{\mathbf{z}} \times \nabla\delta\mu_{\rm N}\right), \tag{3}$$

with $\alpha_{\rm H} = \alpha_{\rm H}^{\rm SJ} + \alpha_{\rm H}^{\rm SS}$, where $\alpha_{\rm H}^{\rm SJ} = \hbar\bar{\eta}_{\rm so}/(3mD)$ is the side jump (SJ) contribution, and $\alpha_{\rm H}^{\rm SS} = (2\pi/3)\bar{\eta}_{\rm so}N(0)V_{\rm imp}$ is the skew scattering (SS) contribution, $\bar{\eta}_{\rm so} = k_{\rm F}^2\eta_{\rm so}$ is the dimensionless spin-orbit coupling parameter, $k_{\rm F}$ is the Fermi momentum, and $V_{\rm imp}$ is the impurity potential.

Equations (2) and (3) indicate that the spin current $\mathbf{j}_s$ induces the transverse *charge* current (charge Hall current) $\mathbf{j}_q^{\rm H}$, whereas the charge current $\mathbf{j}_q$ induces the transverse *spin* current (spin Hall current) $\mathbf{j}_s^{\rm H}$. Equation (1) is expressed in the matrix forms

$$\begin{bmatrix} J_{q,x} \\ J_{s,y} \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & -\sigma_{xy} \\ \sigma_{xy} & \sigma_{xx} \end{bmatrix} \begin{bmatrix} E_x \\ -\nabla_y\delta\mu_{\rm N}/e \end{bmatrix}, \tag{4}$$

$$\begin{bmatrix} J_{s,x} \\ J_{q,y} \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & -\sigma_{xy} \\ \sigma_{xy} & \sigma_{xx} \end{bmatrix} \begin{bmatrix} -\nabla_x\delta\mu_{\rm N}/e \\ E_y \end{bmatrix}, \tag{5}$$

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where $\sigma_{xx} = \sigma_{\rm N}$ is the longitudinal conductivity and σ_{xy} is the Hall conductivity contributed from SJ and SS: $\sigma_{xy} = (\alpha_{\rm H}^{\rm SJ} + \alpha_{\rm H}^{\rm SS})\sigma_{\rm N} = \sigma_{xy}^{\rm SJ} + \sigma_{xy}^{\rm SS}$ with

$$\sigma_{xy}^{\rm SJ} = \frac{e^2}{\hbar}\eta_{\rm so} n_e, \qquad \sigma_{xy}^{\rm SS} = \alpha_{\rm H}^{\rm SJ}\frac{n_e}{n_{\rm imp}}\left[N(0)V_{\rm imp}\right]^{-1}, \tag{6}$$

where n_e is the carrier (electron) density and $n_{\rm imp}$ is the impurity concentration. Note that $\sigma_{xy}^{\rm SJ}$ is *independent* of impurity concentration $n_{\rm imp}$.

The ratio of the SJ and SS Hall contributions is

$$\frac{\sigma_{xy}^{\rm SJ}}{\sigma_{xy}^{\rm SS}} = 2\frac{n_{\rm imp}}{n_e}N(0)V_{\rm imp} = \frac{3}{4\pi}\frac{\hbar}{\epsilon_{\rm F}\tau_{\rm imp}}\frac{1}{N(0)V_{\rm imp}}, \tag{7}$$

where $\tau_{\rm imp}$ is the momentum scattering time and $\epsilon_{\rm F}$ is the Fermi energy. In ordinary non-magnetic metals, the ratio is very small because $n_{\rm imp} \ll n_e$ and $N(0)V_{\rm imp} \sim 1$, so that SS gives the dominant contribution to SHE. However, in very dirty metals or in low-carrier materials such as doped semiconductors with $n_{\rm imp} \sim n_e$, the SJ conductivity is comparable to or even larger than the SS conductivity in SHE.

In the following, we consider a spin-injection Hall device shown in Fig. 1, and concentrate on the spin-current induced SHE. The magnetization of F electrode points to the z direction. When the current I is sent from F to the left side of N, the spin-polarized electrons are injected to create a pure spin current $\mathbf{j}_s$ in N on the right side, where the total charge current is expressed as

$$\mathbf{J}_q = -(\alpha_{\rm H}\sigma_{\rm N}/e)\left(\hat{\mathbf{z}} \times \nabla\delta\mu_{\rm N}\right) + \sigma_{\rm N}\mathbf{E}. \tag{8}$$

where the first term is the Hall current induced by $\mathbf{j}_s$, the second term is the Ohmic current induced by surface charge, and $\alpha_{\rm H} \sim \bar{\eta}_{\rm so}N(0)V_{\rm imp}$ (skew scattering). In the open circuit condition in the transverse direction, where J_q^y vanishes, the nonlocal Hall resistance $R_{\rm H} = V_{\rm H}/I$ becomes

$$R_{\rm H} = \frac{1}{2}\alpha_{\rm H}P_{\rm T}\left(\rho_{\rm N}/d_{\rm N}\right)e^{-L/l_{\rm N}}, \tag{9}$$

in the case of tunnel junction, where $P_{\rm T}$ is the tunneling spin polarization, $\rho_{\rm N}$ is the resistivity, $l_{\rm N}$ is the spin-diffusion length, and $d_{\rm N}$ is the thickness of N. In the case of metallic-contact junction

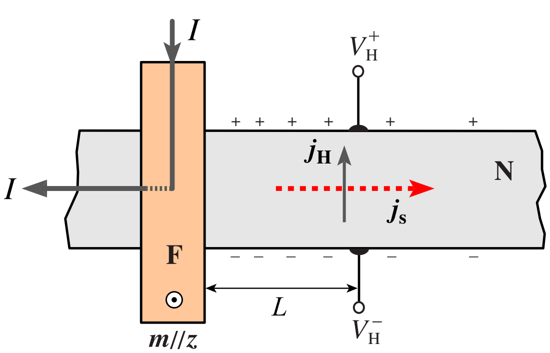

Fig. 1. Spin injection Hall device (top view). The magnetic moment of F is aligned perpendicular to the plane. The spin-current induced Hall voltage $V_{\rm H} = V_{\rm H}^+ - V_{\rm H}^-$ is induced in the transverse direction by injection of pure spin current $\mathbf{j}_s$.

Table 1
Spin-orbit coupling parameter $\bar{\eta}_{\rm so}$ of Cu, Al, and Ag.

	$l_{\rm N}$ (nm)	$\rho_{\rm N}$ ($\mu\Omega$cm)	$\tau_{\rm imp}/\tau_{\rm sf}$	$\bar{\eta}_{\rm so}$
Cu[a]	1000	1.43	0.70×10^{-3}	0.040
Cu[b]	1500	1.00	0.64×10^{-3}	0.037
Cu[c]	546	3.44	0.41×10^{-3}	0.030
Al[d]	650	5.90	0.36×10^{-4}	0.009
Ag[e]	195	3.50	0.50×10^{-2}	0.110

[a]Ref. [2], [b]Ref. [3], [c]Ref. [4], [d]Ref. [2], [e]Ref. [5].

$$R_{\rm H} = \frac{1}{2}\alpha_{\rm H}\frac{p_{\rm F}}{1-p_{\rm F}^2}\left(\rho_{\rm N}/d_{\rm N}\right)\frac{R_{\rm F}}{R_{\rm N}}\sinh^{-1}(L/l_{\rm N}), \tag{10}$$

where $p_{\rm F}$ is the spin polarization of F, $R_{\rm N}$ and $R_{\rm F}$ are the spin resistances of the N and F electrodes: $R_{\rm N} = (\rho_{\rm N}l_{\rm N})/A_{\rm N}$ and $R_{\rm F} = (\rho_{\rm F}l_{\rm F})/A_{\rm J}$ with $A_{\rm N}$ the cross-sectional area of N and $A_{\rm J}$ the contact area between N and F. Usually, $R_{\rm N}$ is one or two orders of magnitude larger than $R_{\rm F}$ [12]. Recently, the spin-current induced AHE have been measured using spin injection techniques [13,14].

It is worthwhile to make the product $\rho_{\rm N}l_{\rm N}$, which is related to the spin-orbit coupling parameter $\bar{\eta}_{\rm so}$ as

$$\rho_{\rm N}l_{\rm N} = \frac{\sqrt{3}\pi}{2}\frac{R_{\rm K}}{k_{\rm F}^2}\sqrt{\frac{\tau_{\rm sf}}{\tau_{\rm imp}}} = \frac{3\sqrt{3}\pi}{4}\frac{R_{\rm K}}{k_{\rm F}^2}\frac{1}{\bar{\eta}_{\rm so}}, \tag{11}$$

where $R_{\rm K} = h/e^2 \sim 25.8\,{\rm k}\Omega$ and $\tau_{\rm sf}$ is the spin-flip scattering time. The formula (11) provides a method for extracting the physical parameters of spin-orbit scattering in nonmagnetic metals. Using experimental data of $\rho_{\rm N}$ and $l_{\rm N}$ in Eq. (11), we obtain the value of the spin-orbit coupling parameter $\bar{\eta}_{\rm so} = 0.01$–$0.04$ in Cu, Al, and Ag as listed in Table 1. Therefore, Eqs. (9) and (10) yields $R_{\rm H}$ of the order of 0.1–1 mΩ, indicating that the spin-current induced SHE is observable by using nonlocal spin-injection Hall devices.

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